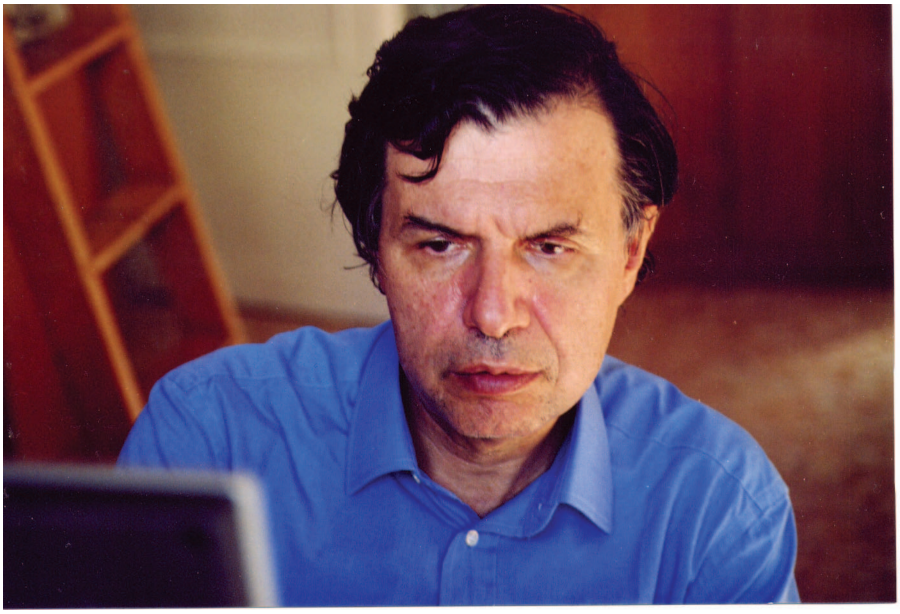
Profile of Giorgio Parisi



Giorgio Parisi

Physicist Giorgio Parisi has no problem stretching the conventions of mathematics if it helps him solve a difficult physics problem. Once, while struggling to develop a mathematical model for a complicated system, he found that turning basic concepts inside-out was the only way to crack the puzzle. Parisi explains that it was as if he needed to figure out the number of distinct ways that a handful objects could be placed in a row. The mathematics would not budge, until he decided to introduce the idea of a "half-object." "Now, a half-object is something that does not make sense," Parisi admits. "When physicists use mathematics, they use it in a looser way."

Parisi's idea of the half-object brought him acclaim in the field of disordered systems, and nearly a quarter of a century later, mathematicians agreed that his innovation was correct. Parisi's accomplishments span many fields of modern physics, including elementary particles, statistical mechanics, mathematical physics, and, especially, disordered systems. Professor of Quantum Theories at the University of Roma I, "La Sapienza," in Rome, Parisi was elected as a correspondent fellow of the Accademia dei Lincei in 1992, a fellow of the French Academy in 1993, and a foreign associate of the National Academy of Sciences in 2003. His many honors include the Feltrinelli Prize for physics in 1986, the Boltzmann Medal in 1992, the Italgas Prize in 1993, the Dirac Medal and Prize in 1999, the Ënrico Fermi Award in 2002, and the Dannie Heinemann Prize in 2005. In his Inaugural Article (1), published in this issue of PNAS, Parisi reviews recent advances in the study of spin glasses and structural fragile glasses and discusses problems remaining in the field.

Bringing High Energy to Physics

If Parisi had followed in his family's footsteps, he might be working with steel and concrete instead of string theory and quarks. His father and grandfather were both construction workers, and the young Parisi was encouraged to become an engineer. Instead, Parisi was drawn to the complicated abstractions he read in books of popular science and mathematics. "I felt I wanted to do something scientific because it was challenging," he recalls.

Parisi was torn between majoring in physics and mathematics at the University of Roma, "La Sapienza." At the time, he could see that the field of physics had made remarkable progress over the first half of the 20th century, he says, but mathematics' analogous accomplishments were more mysterious. Parisi decided to study physics. As soon as he started classes, he knew he wanted to do research in physics. The highest degree offered in Italy at the time was equivalent to a single year of doctoral studies, and Parisi took full advantage of the year after receiving his bachelor's degree at the University of Roma. He worked with Nicola Cabibbo, a high-energy physicist who was "by far the most brilliant theoretician in Rome at that time," Parisi says.

Cabibbo's and Parisi's research involved high-energy particle physics, widely considered "the most challenging and most important thing" to study at the time, Parisi says. He graduated from the University of Roma in 1970 and went immediately to work at the Laboratori Nazionali di Frascati, a laboratory with a particle accelerator near Rome. He worked there for 10 years before returning as a full professor of theoretical physics at the University of Roma II, "Tor Vergata," in Rome. In 1992, he returned to the University of Roma I, "La Sapienza," as a professor of quantum theories, where he remains today.

Frustration in Spin Glasses

Parisi's arguably best work involves a special type of magnetic alloy called spin glass, a field he stumbled upon in December 1978. At the Frascati laboratory, he studied an "exotic problem" that cropped up in his work in high-dimensional gauge theory, a field of study that describes how certain physical theories share special mathematical properties. For this particular problem, Parisi wanted to use the replica technique, a mathematical tool that researchers can sometimes use to reduce the complexity of physical system models. But Parisi learned that the replica technique gave inconsistent results when applied to spin glass systems (2). "I decided before I use the technique for myself, I would like to understand why it did not work for spin glasses. I started to study, and the first inquiry convinced me that there was something wrong," he says.

Spin glasses are particularly interesting to theoreticians because they are "magnetically frustrated" and represent the ultimate disordered system. Spin glasses consist of a crystalline material (such as copper) into which a small number of magnetic atoms (such as manganese) have been placed at random. Magnetic atoms always have a "spin," or orientation. However, unlike a pure ferromagnet, which has orderly magnetic atoms, the spins in a spin glass are frozen in random directions.

This is a Profile of a recently elected member of the National Academy of Sciences to accompany the member's Inaugural Article on page 7948.

Because these materials represent such complex systems, researchers in the 1970s struggled to develop a simple mathematical approximation for spin glasses in the way that they had developed mean field approximations for ferromagnets. When David Sherrington and Scott Kirkpatrick attempted to apply mean field theory developed by Samuel Edwards and Philip Anderson to infinite range spin glasses, they realized that it yielded inconsistent solutions showing negative entropy at extremely low temperatures (2, 3). "I found the problem very, very interesting," Parisi says. He began to study spin glasses "in a concentrated way," he says, hoping to resolve the crisis surrounding the models.

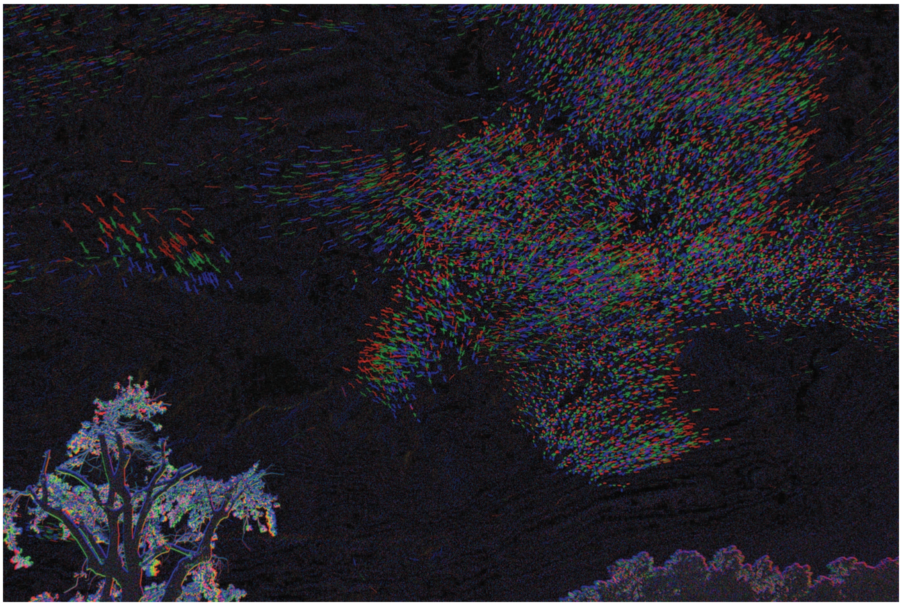
Breaking the Replica Symmetry

The mathematical details behind spin glasses are admittedly "very bizarre," says Peter Young, professor of physics at the University of California, Santa Cruz. Applying the mean field theory to spin glasses first requires creating "replicas" of the system and then breaking these replicas into groups in a way that takes advantage of some mathematical symmetry among them. The original applications of the mean field theory to spin glasses "broke the symmetry" in a simple way that yielded a single-order parameter, but this method led to the inconsistent entropy results.

A novel way of breaking the symmetry thus was needed. A complication was that the method required the number of replicas be forced to approach zero. "It's a strange mathematical device. Very improper mathematics, really," says Young. As a result, the symmetry could potentially be broken in an infinite number of ways, and it was not clear how to proceed.

Parisi then entered the spin glass fray with an idea that was "a mark of genius," Young says (4). "He divided the replicas into groups, and then he divided these groups into subgroups, and those subgroups into smaller subgroups, and so on. And the net result is that you get not one but an infinite number of order parameters," Young explains. This infinite subgrouping solved the problem of breaking the symmetry so that the number of replicas tended to zero, and it turned out that a mathematical function characterized the infinite number of order parameters. "At the end you get something that is mathematically respectable. It's just amazing that it works," says Young.

Parisi also showed that the entropy of the system seems to go to zero at zero temperature and so was more consistent than were previous results. Further work revealed that the function characterizing the infinite number of order parameters was related to the probability distribution of the system's order parameter of the system as it fluctuates through its complicated energy landscape (5). Most researchers now believe that the Parisi solution is in fact an exact solution and not merely an approximation. Parisi's citation for the award of the Boltzmann Medal in 1992 stated that his work "forms one of the most important breakthroughs in the history of disordered systems."



Graphical elaboration of three subsequent photographs of starling flocks.

"When physicists use mathematics, they use it in a looser way."

Disordered systems crop up in more than just magnetic alloys, and the lessons learned from spin glasses have extended to other fields. In particular, using replicas and breaking the symmetry among them has been useful in the computer science field of combinatorical optimization, in which researchers need to maximize or minimize a function of many variables subject to constraints (6). Many of the papers written on spin glasses have been compiled into the book *Spin Glass Theory and Beyond*, which Parisi coauthored (7).

In his PNAS Inaugural Article (1), Parisi reviews recent theoretical results for spin glasses and for the actual glasses known as structural fragile glasses. He discusses unsolved problems for which he sees a great need for new research, including gaining better quantitative predictions and a more precise comparison between theory and experiments. Parisi also reviews other applications, including neural networks and constraint satisfaction problems in computer science.

Physics for the Birds

Although noteworthy, Parisi's work on spin glasses is only one part of his research palette. "I have a tendency to work on different subjects at the same time, because in order to get an idea, it takes time. You have to digest the concepts," he says. He has made advances in a number of fields, including elementary particles, statistical mechanics, string theory, biophysics, and computer design (both software and hardware).

Parisi's diverse research contributions include the study of scaling violations in deep inelastic processes [the Altarelli–Parisi equations (8)], a simple explanation for quark confinement based on the superconductor's flux confinement model (9), the introduction of multifractals in turbulence and in strange attractors (10), the study of idiotypic network theory for antibodies in theoretical immunology (11), and the Array Processor Expansible (APE) project (12).

More recently, Parisi has studied highly complex, disordered systems that even nonscientists can appreciate: whirling flocks of birds. “Starlings are very interesting because they make very fast movements in the air. They move very straight, very fast, and this is done by thousands and thousands of them,” Parisi says. “One of the problems is how do they communicate in order to have this collective movement done together?”

Parisi and 20 colleagues spent the past winter studying starlings in action. Parisi estimates having taken approximately 100,000 photographs of flocks in the air. Now the group is writing computer programs to create a 3D reconstruction of the flocks and hopes to have results soon. Starling flocks provide a convenient, measurable example of a complex system. “They may seem very far from spin glasses, but there is something in common,” Parisi says. “What they share, and what is very interesting, is how complex behaviors arise. This is a theme recurrent in physics and biology, and most of the research that I have done is to get at this thing: how complex collective behavior may arise from elements that each have a simple behavior.”

Regina Nuzzo, *Science Writer*

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